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Improvement of Human Safety in Fault-Tolerant Human and Robot Collaboration Using Convex Optimization and Receding Horizon Control

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Robotics in industries: 2016

- 34,606 robots ($1.9 billion) were ordered in North America: growth of 10%
  - The automotive industry: 25 % growth
  - Assembly applications: 61% growth
  - Spot welding: 24% growth
  - The food and consumer goods industry: 32% growth

- Robotic Industries Association

Robotics in industries: 2025

- Replacing 16% of jobs in US
- Creating nearly 9,000,000 (9%) new jobs in new fields like robot monitoring, data science and content curation
- Net value: Impacting 7% of jobs

- Forrester Research

Robotics in industries

What if a task needs the intelligence and flexibility of human and accuracy and repeatability of a robot?

Collaborative Robots

Collaborative Robots

- Designed to be safe around people
- Easy to program, n via a smartphone or tablet
- Easy to task as neede
- In work
- Lightweight
- Simpler than more aditional robots
- Cheaper to buy, operate and maintain

FME Feinmechanik, Switzerland

Interactive Robotics Lab, ASU

Safety

- Accidents happen when the human worker is inside the work cell
  - Human interferes with robot normal motion
  - A failure in robot causes sudden and harmful motion

The Telegraph, July 2015:
A robot has killed a contractor at one of Volkswagen's production plants in Germany where a 22-year-old man was setting up the stationary robot.

The Times of India, August 2015:
Sharp welding sticks jutting out of the robotic arm of a machine pierced a worker killing him at a factory. The worker had moved too close to the robot while adjusting a metal sheet that had come unstuck..

Safety

- Robophobia: An anxiety disorder in which sufferers have an "irrational fear of robots, drones, robot-like mechanics, or artificial intelligence."

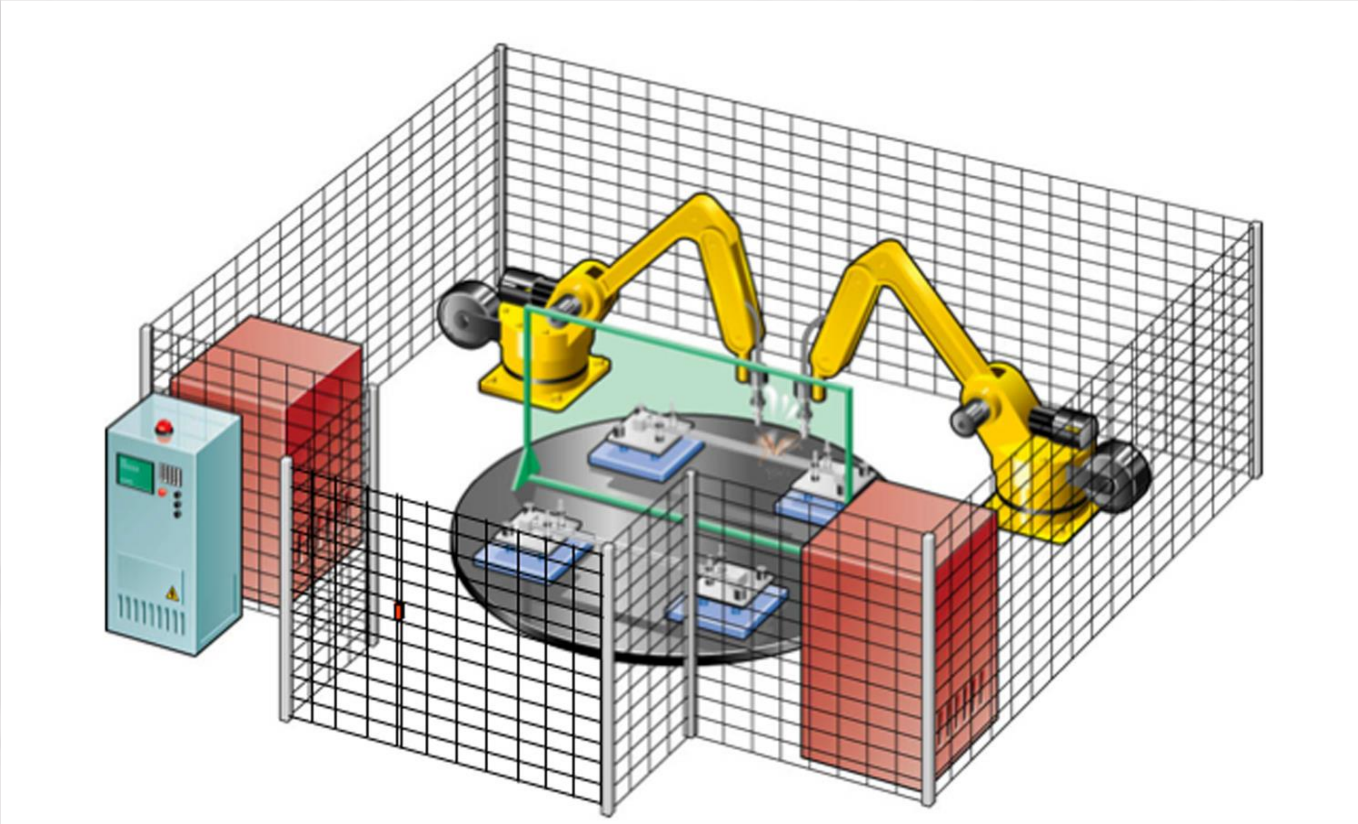
Psychologist Dr. Graham Davey, 1997

- Symptoms: panic attacks, sweating, anxiousness, discomfort, kicked off by either the sight of a robot, being near a robot, or even just talking about robots.

In 1997, 20% of the world's population were suffering from robophobia.

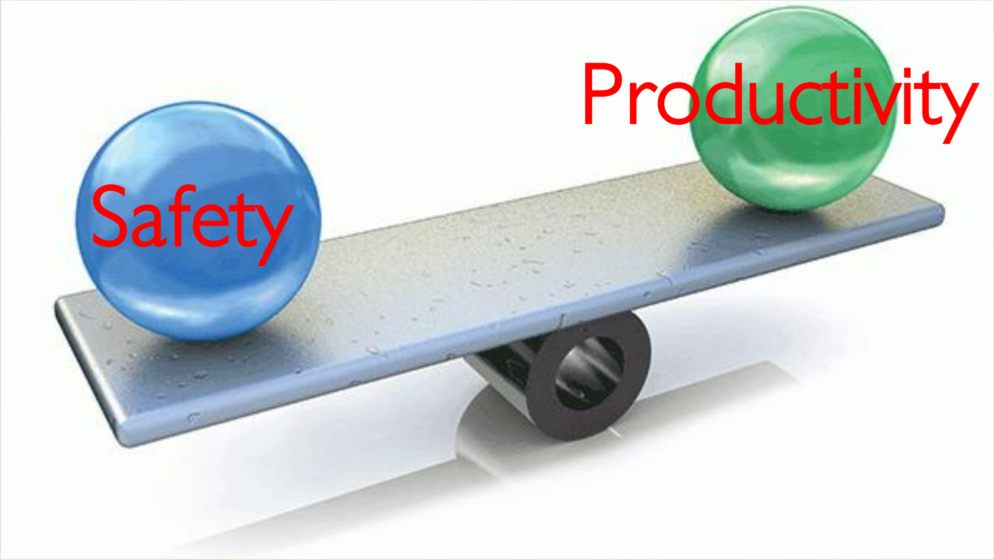
Safety

- Solutions:
  - Physical safety barriers
  - Limits on robot motion
  - Limits on robot forces
  - Proper installation of robot
  - Use force/torque controls



Productivity?

Safety vs Productivity



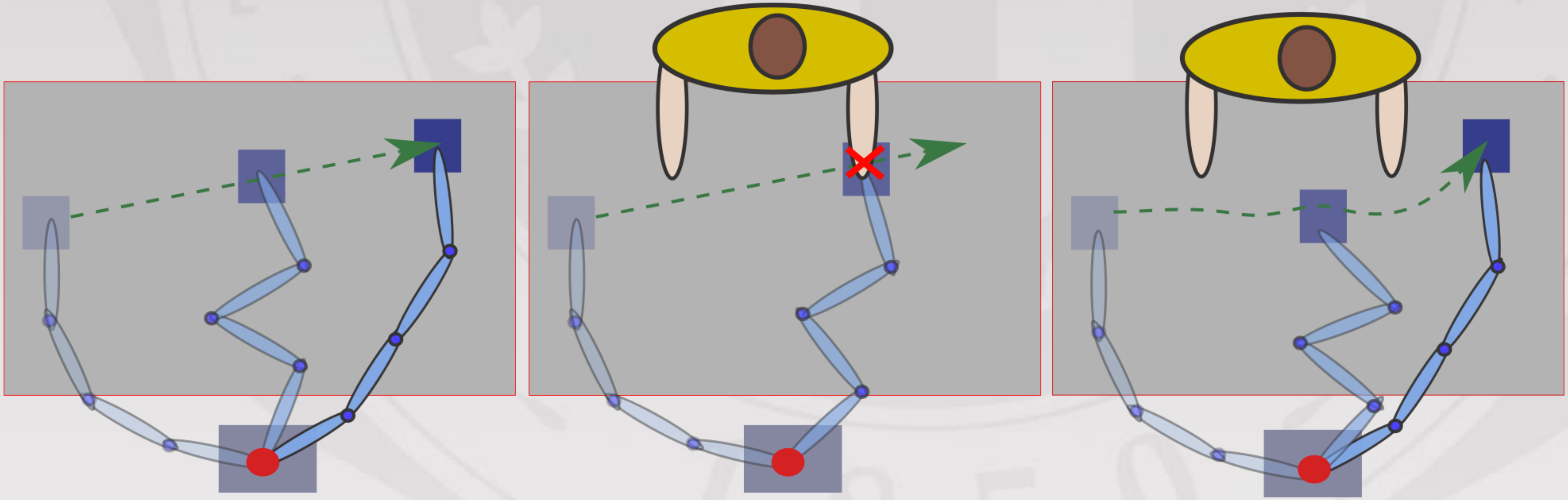
Safety first, but also be more productive

Collision-free motion planning algorithm

Recovery from failure

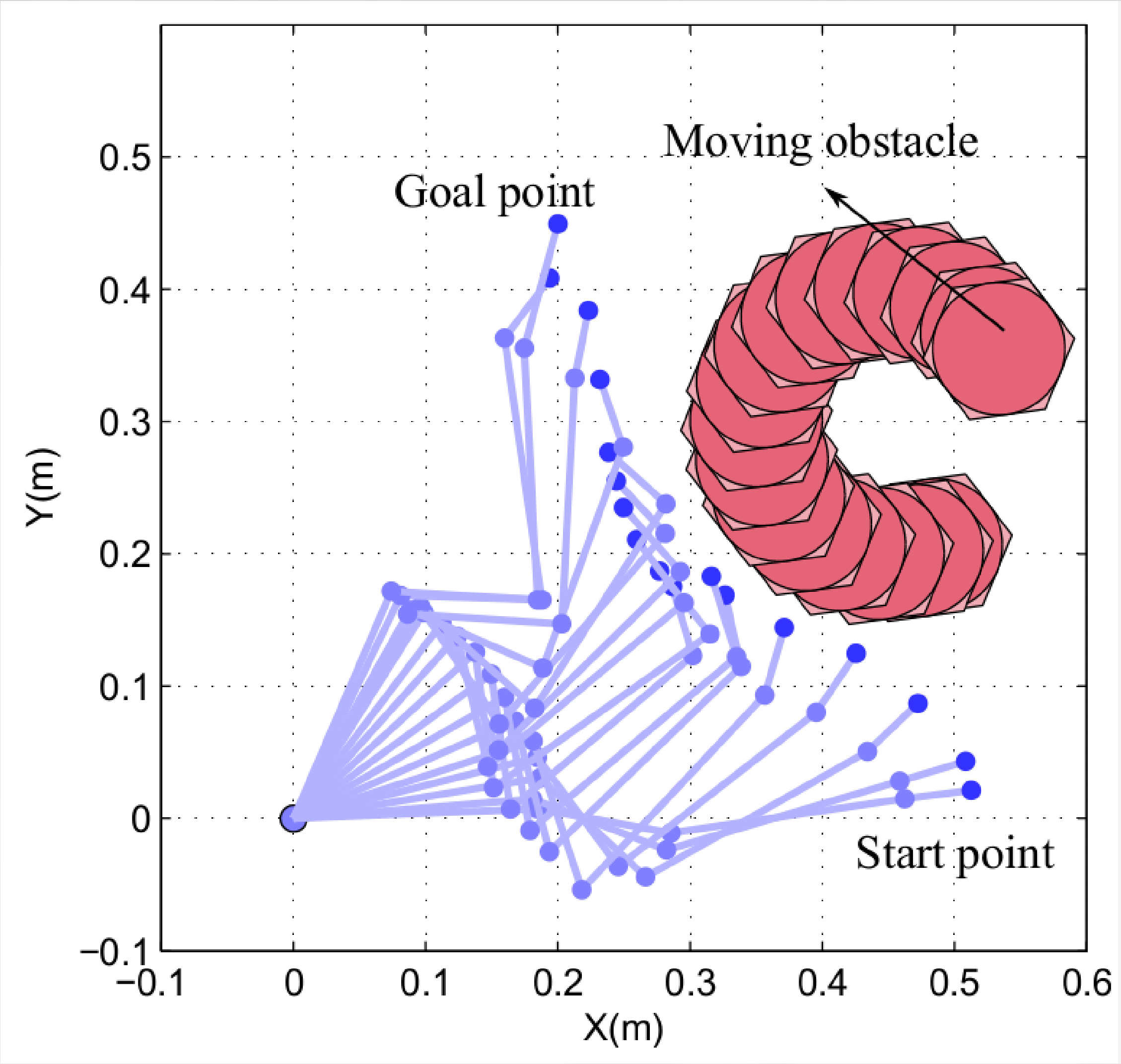
Problem & Solution

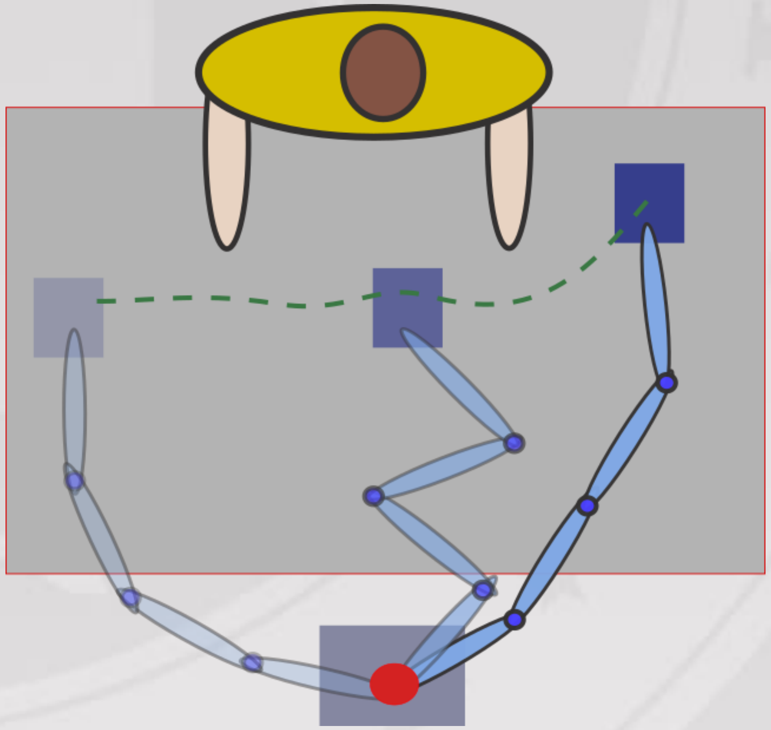
- Optimal path planning for end-effector and collision avoidance



Problem & Solution

- Optimal path planning for end-effector and collision avoidance

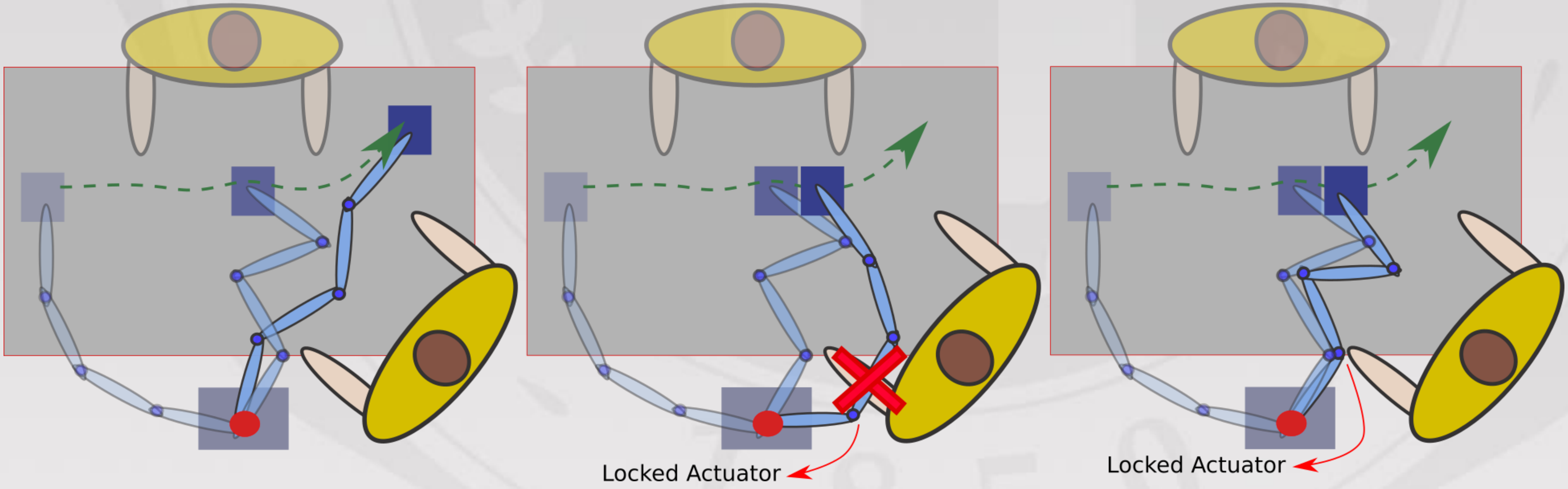




Sabbagh Novin, R., Tale Masouleh, M., & Yazdani, M. (2016). Optimal motion planning of redundant planar serial robots using a synergy-based approach of convex optimization, disjunctive programming and receding horizon. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, *230*(3), 211-221.

Problem & Solution

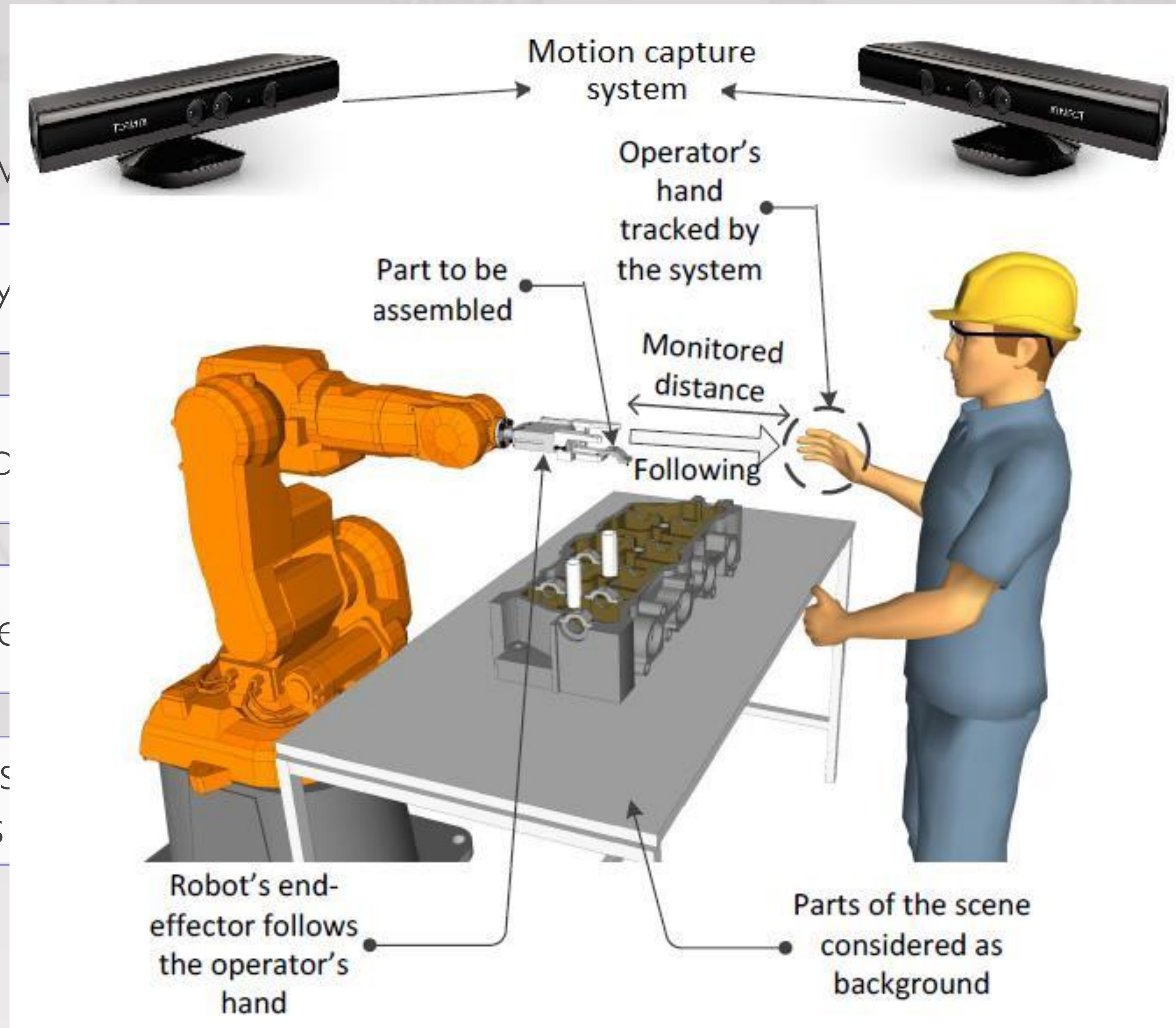
- Optimal fault-tolerant trajectory planning for joints and collision avoidance



Problem & Solution

Develop nev

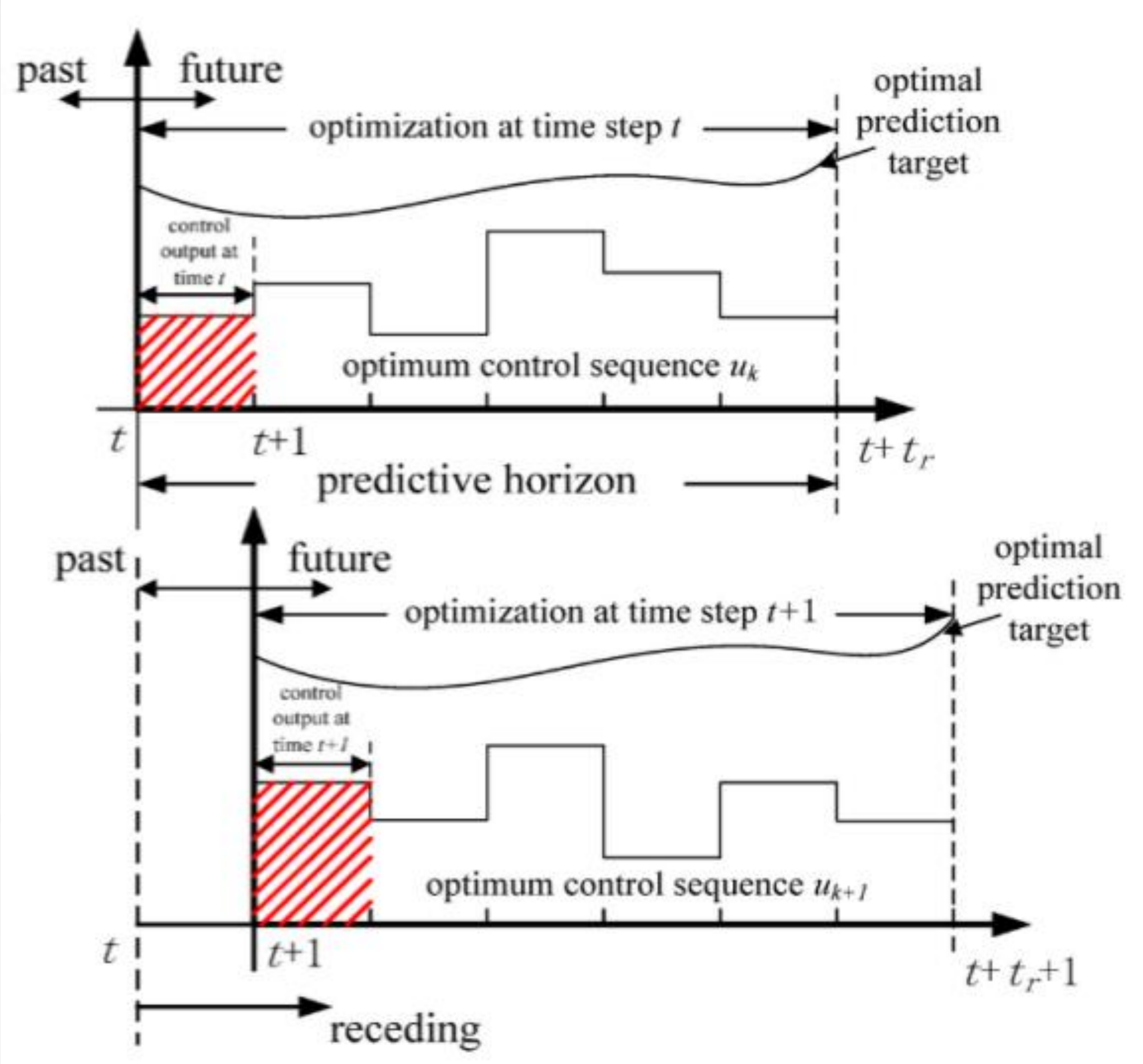
- Optimally
- Avoids cc
- Complete
- Minimizes actuators



Methods And Approaches

- Receding Horizon Control
  - Predicts and plans for next K steps in each iteration
  - Executes only the first step in each iteration
  - Re-plans after each step

✓ Make a smooth trajectory
✓ Decrease computational time



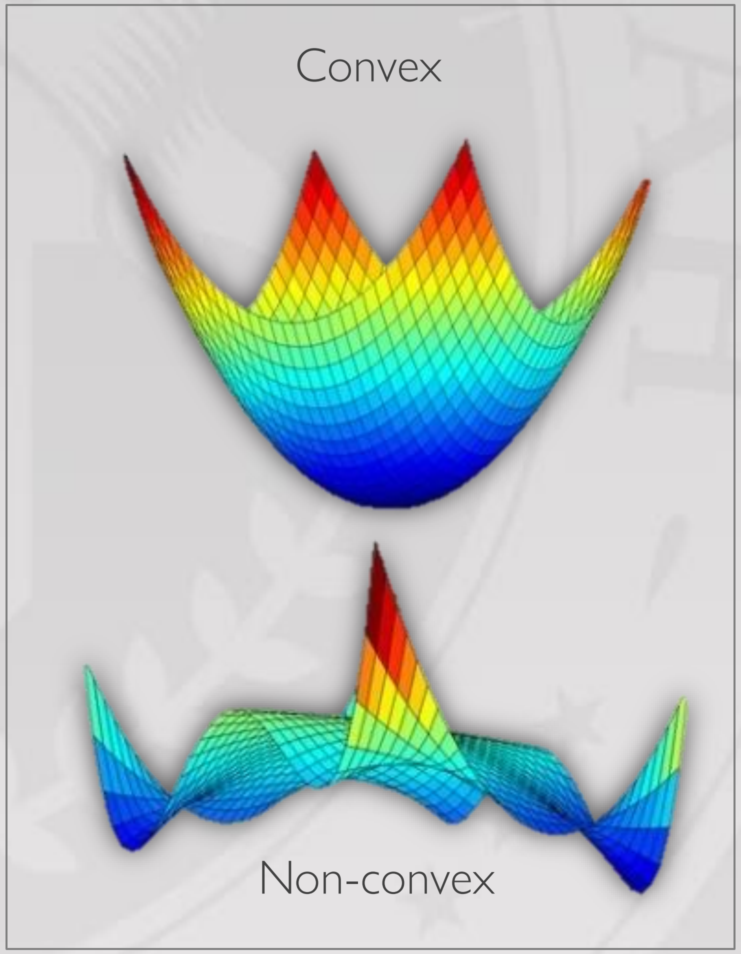
Changbin Hu 2015

Methods And Approaches

- Convex Optimization

$$\begin{aligned} \min \quad & f_0(x) \\ s.t. \quad & f_i(x) < 0 \\ & h_j(x) = 0 \end{aligned}$$

  - It is convex when:
    - The objective function is convex
    - The inequality constraint functions are convex
    - The equality constraint functions are affine
  - Guarantees global optimality
  - Used GUROBI optimization package (fastest solver available now)



GUROBI OPTIMIZATION

Methods And Approaches

- Objective function:
  - Minimum path $$\min \sum_{i=1}^{h}\sum_{j=1}^{p}\left\|z_j(i+1)-z_j(i)\right\|_2^2$$
  - Minimum joints velocity jumps $$\min \sum_{i=1}^{h}\left\|\ddot{q}_j\right\|_2^2$$
  - Minimum end-effector tracking error $$\min \sum_{i=1}^{h}\left\|z_r(i)-z_{n_l,m}(i)\right\|_2^2$$

$$\min \quad w_1\sum_{i=1}^{h}\sum_{j=1}^{p}\left\|z_j(i+1)-z_j(i)\right\|_2^2 + w_2\sum_{i=1}^{h}\left\|z_r(i)-z_{n_l,m}(i)\right\|_2^2 + w_3\sum_{i=1}^{h}\left\|\ddot{q}_j\right\|_2^2$$

Methods And Approaches

- Constraints
  - Robot kinematics

$$A_{cs,j}(i)(z_{j,m}(i) - z_{j-1,m}(i)) \leq b_{cs,j}(i)$$

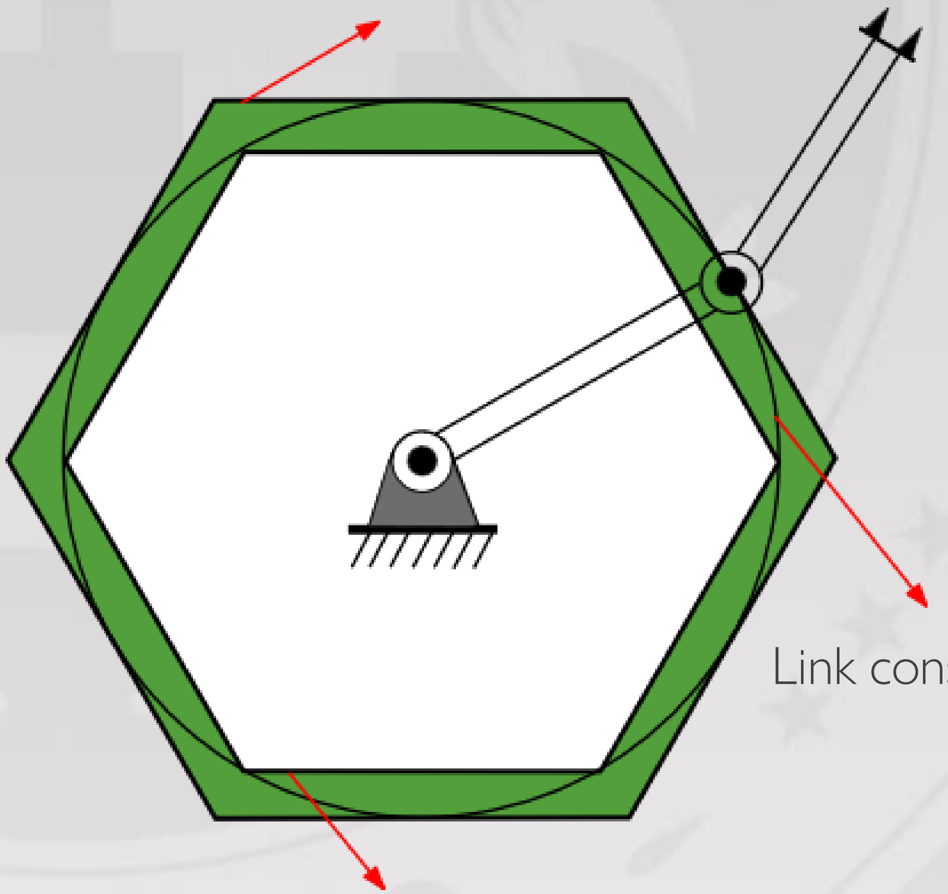
$$A_{is,j}(i)\left(z_{j,m}(i) - z_{j-1,m}(i)\right) \geq b_{is,j}(i) + \left(u_j(i) - 1\right)M$$

$$\sum_{s=1}^{n_{is}} u_{j,s}(i) \geq 1$$

  - Obstacle avoidance

$$A_O(i)z_{j,k}(i) \geq b_O(i) + (v(i) - 1)M$$

$$\sum_{s=1}^{n_{is}} v_s(i) \geq 1$$



Methods And Approaches

- Constraints
  - Actuator failure modeling

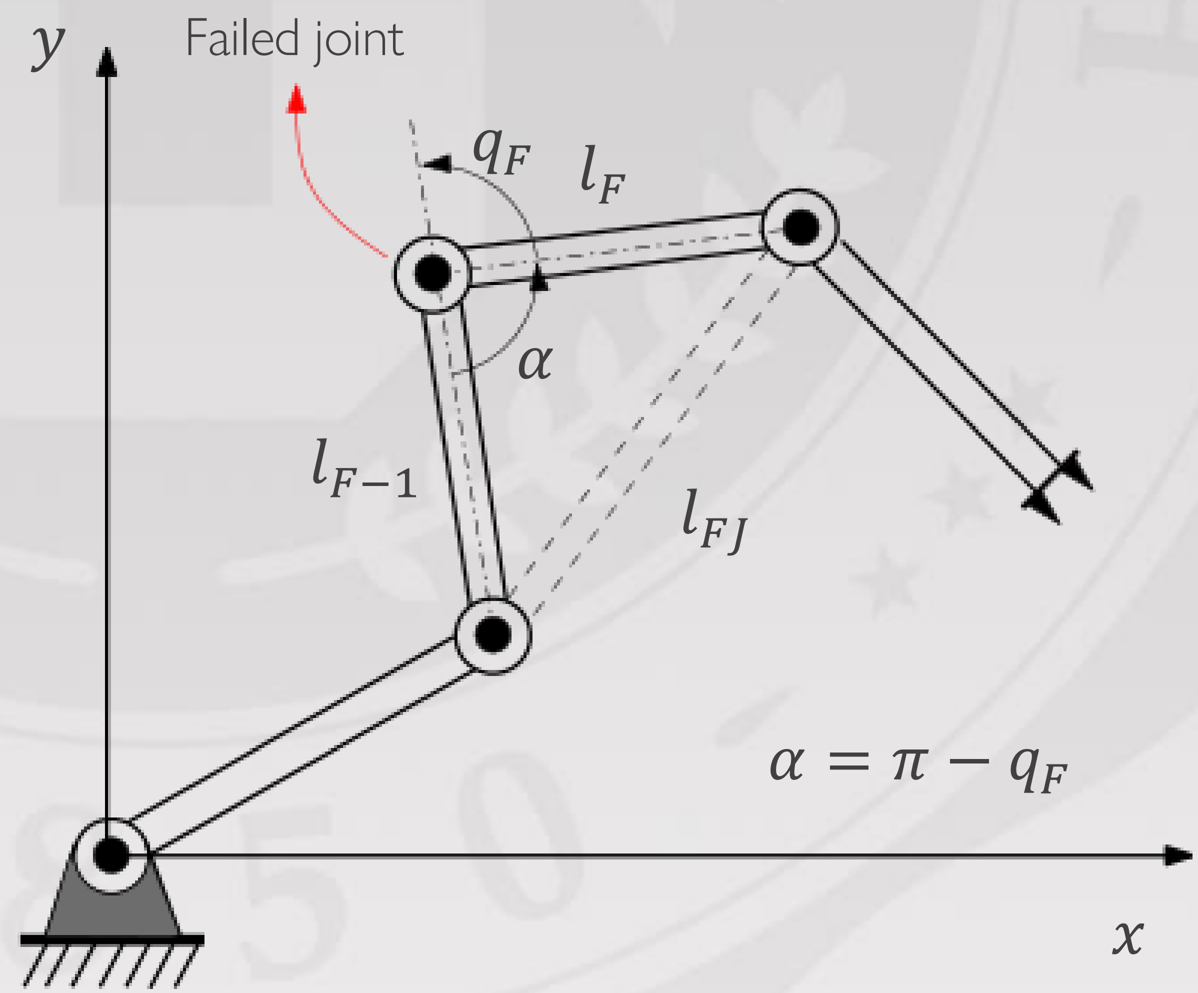
$$A_{cs,F}(i)(z_{j,m}(i) - z_{F-2,m}(i)) \leq b_{cs,F}(i)$$

$$A_{is,F}(i)\left(z_{F,m}(i) - z_{F-2,m}(i)\right) \geq b_{is,F}(i) + (u_F(i) - 1)M$$

$$\sum_{s=1}^{n_{is}} u_{F,s}(i) \geq 1$$

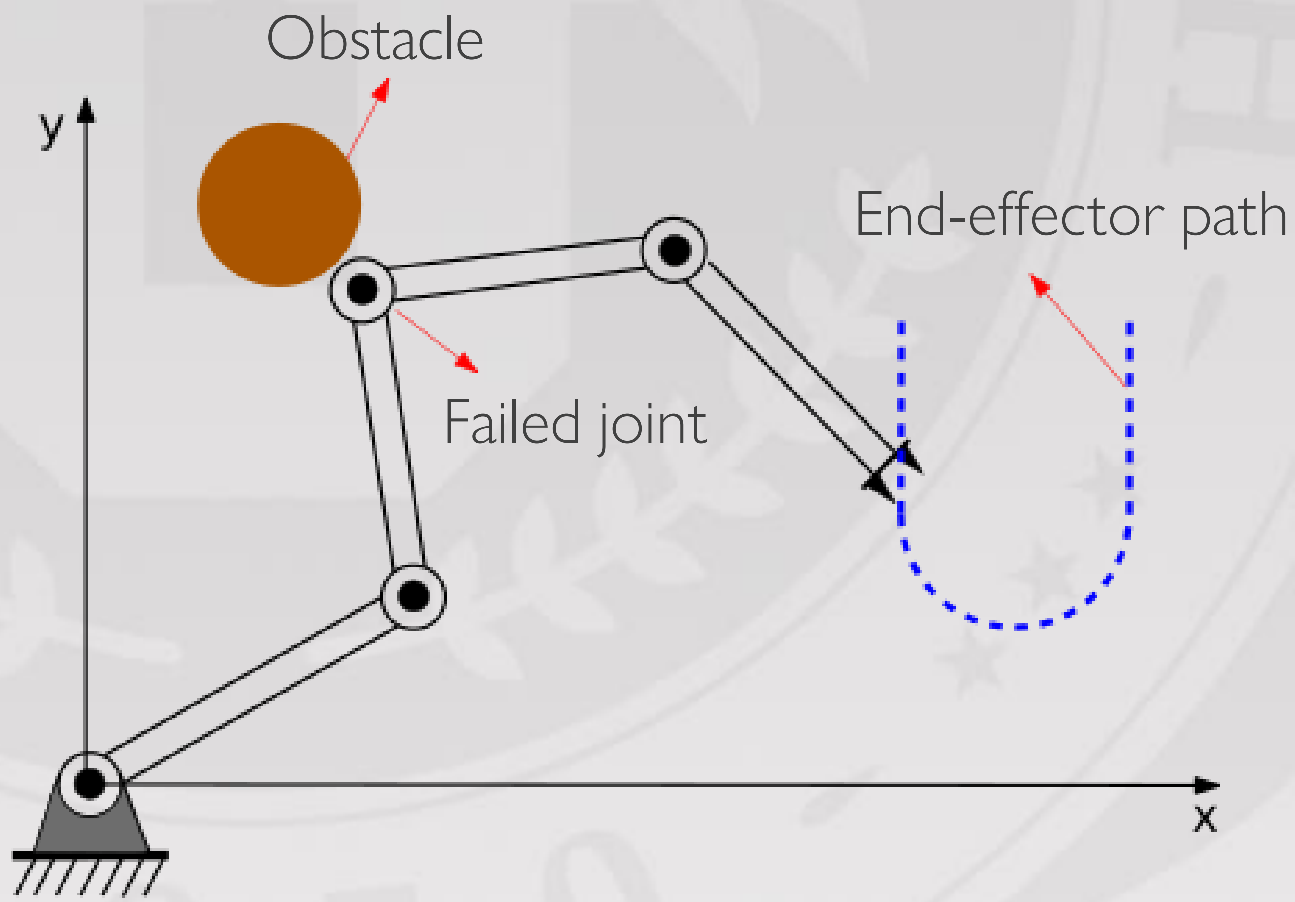
  - Velocity bounds

$$\left|\frac{z_{j,m}(i+1) - z_{j,m}(i)}{\Delta t}\right| \leq v_{j,max}$$



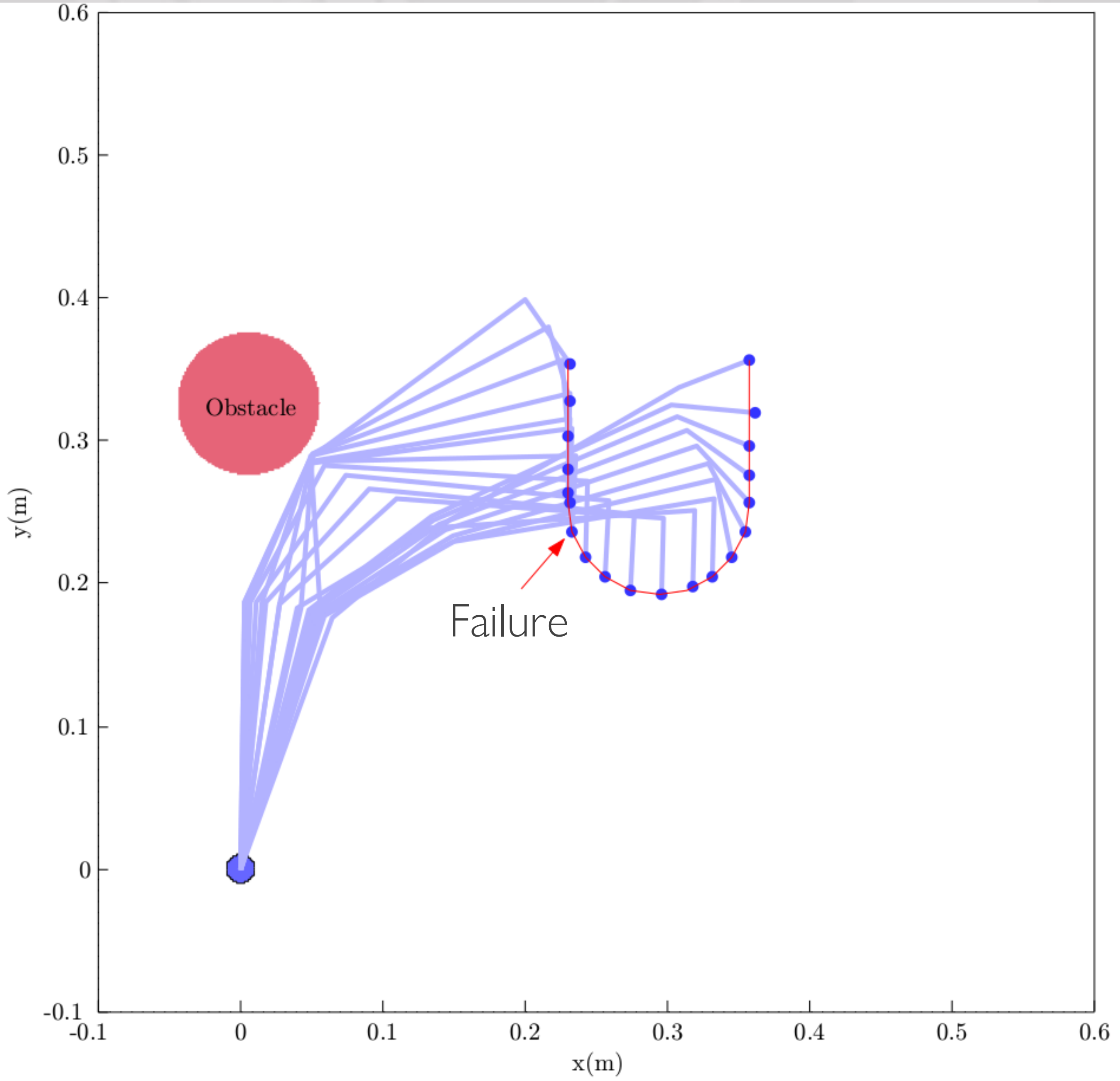
Simulation and results

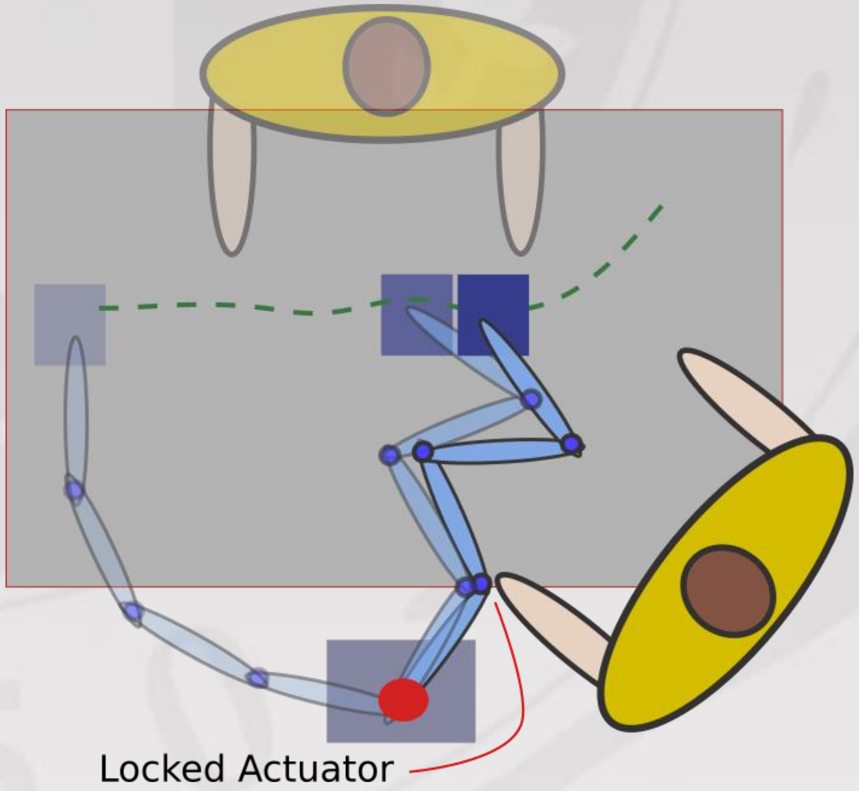
- Planar 4-DOF robot
- End-effector trajectory: U-shaped
- 3rd joint fails (locks) at *t=14* sec
- Human as obstacle



Simulation and results

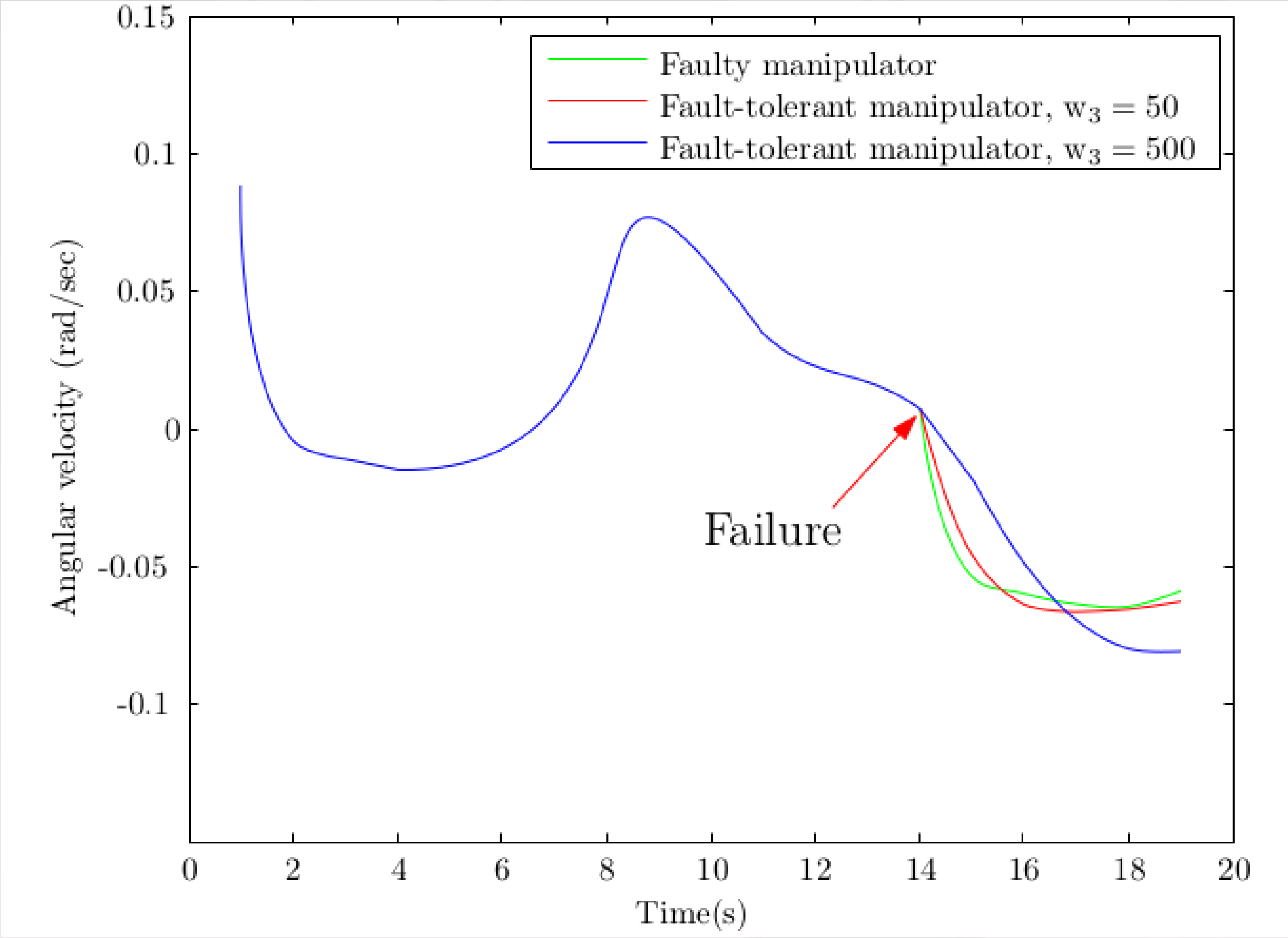
- Task completion and obstacle avoidance
  - o 3rd joint locks at t=14 sec



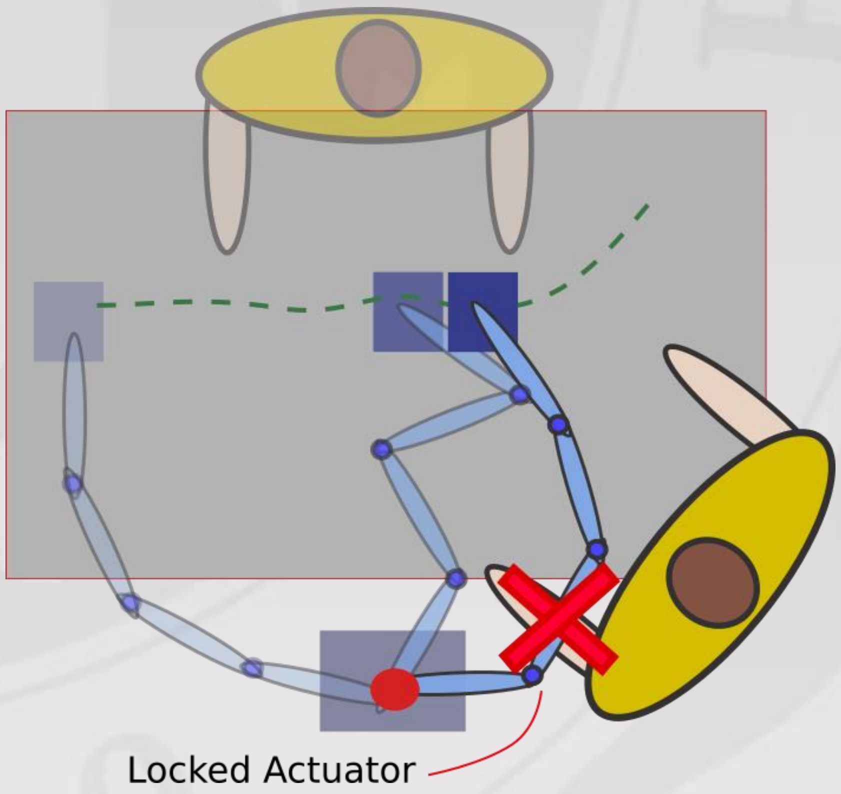


Simulation and results

- Minimize velocity jumps

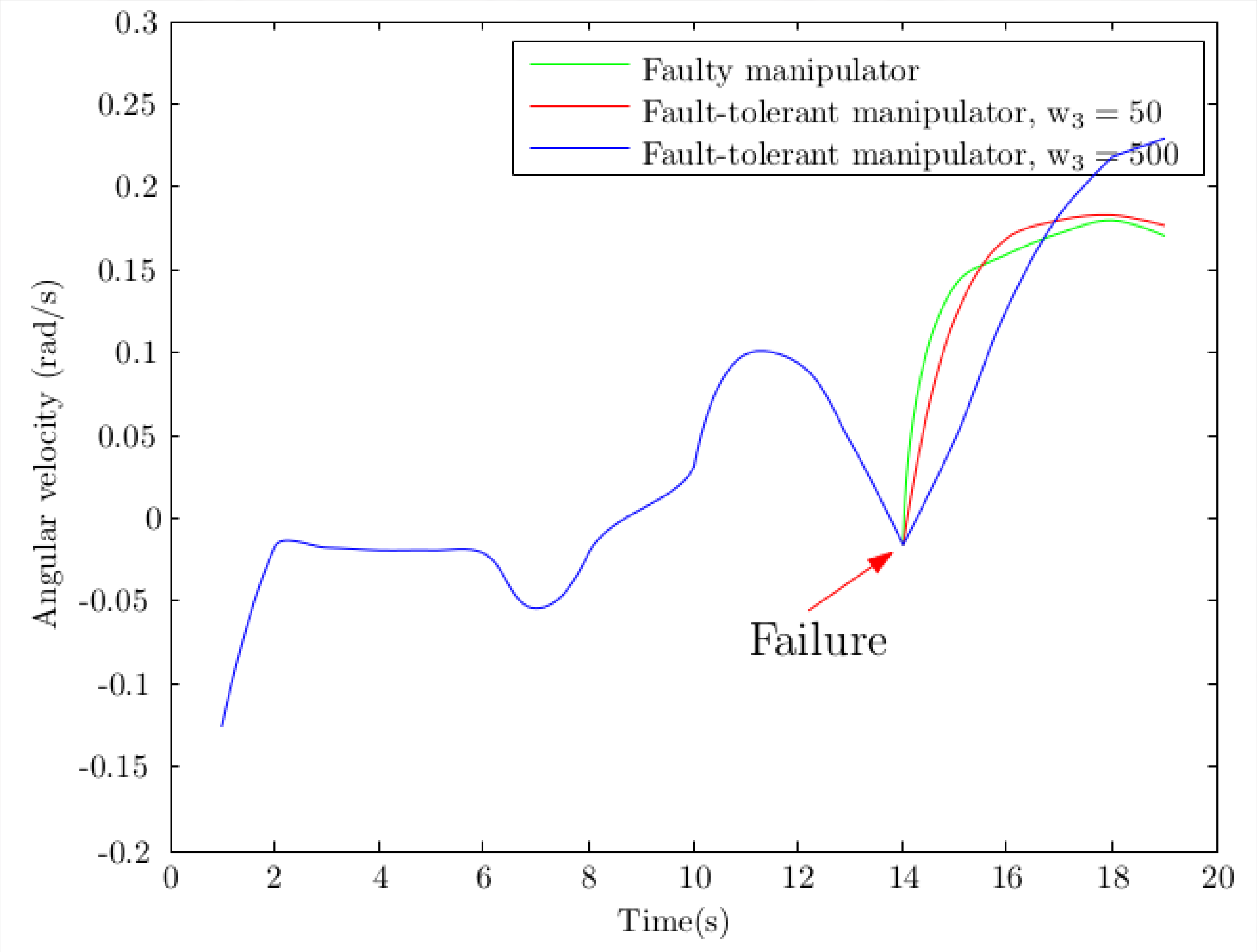


1st joint

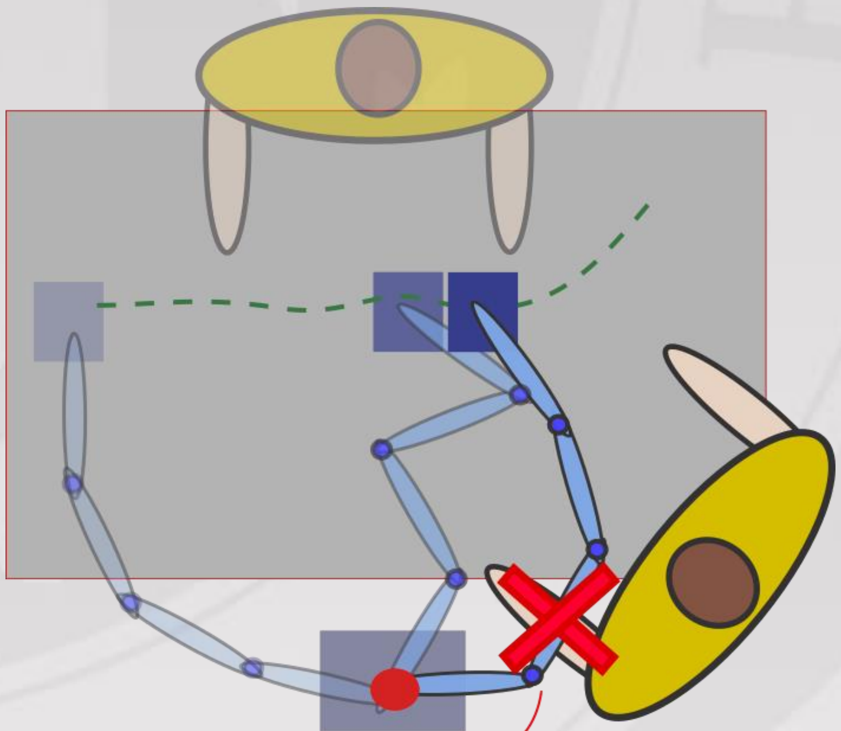


Simulation and results

- Minimize velocity jumps

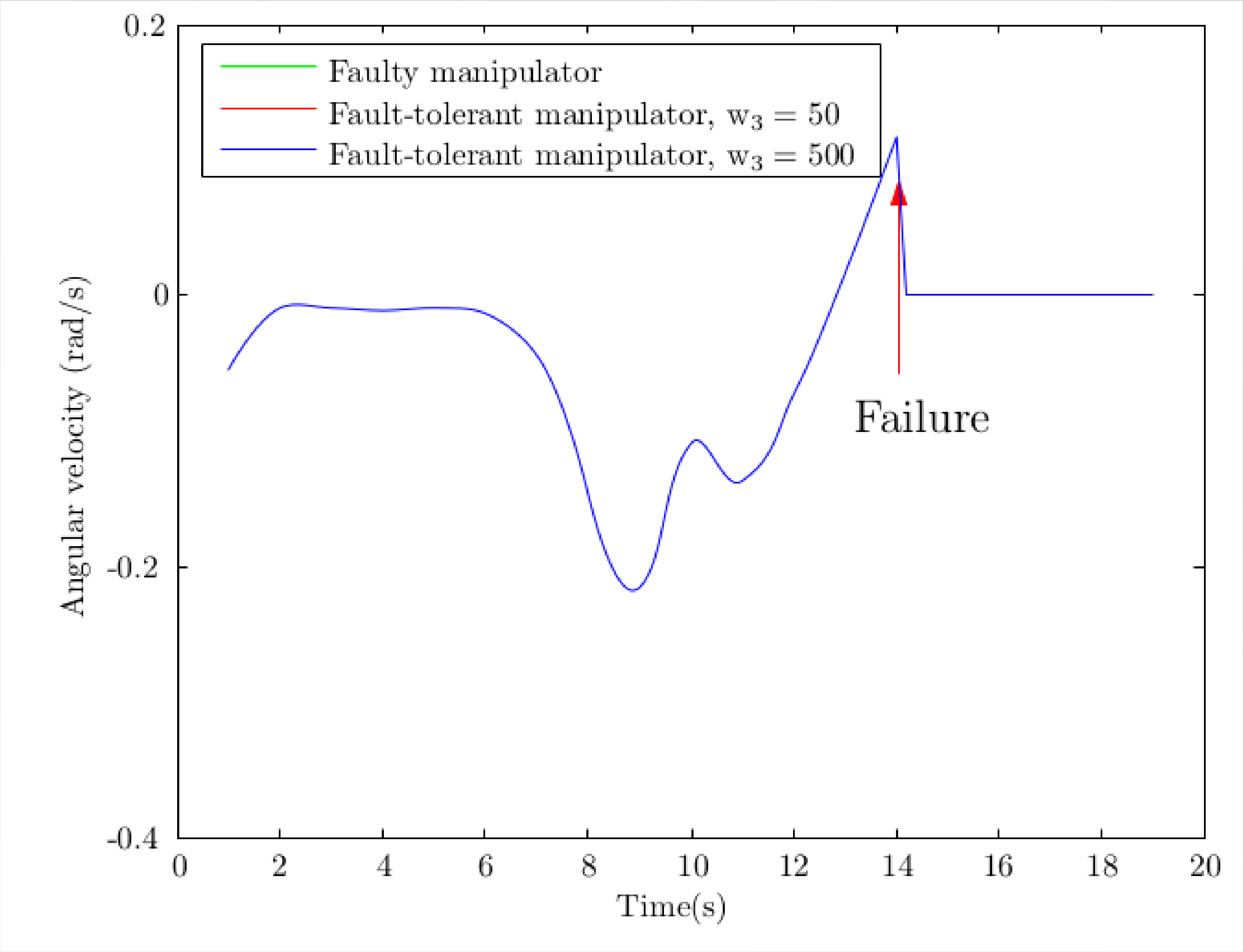


2nd joint

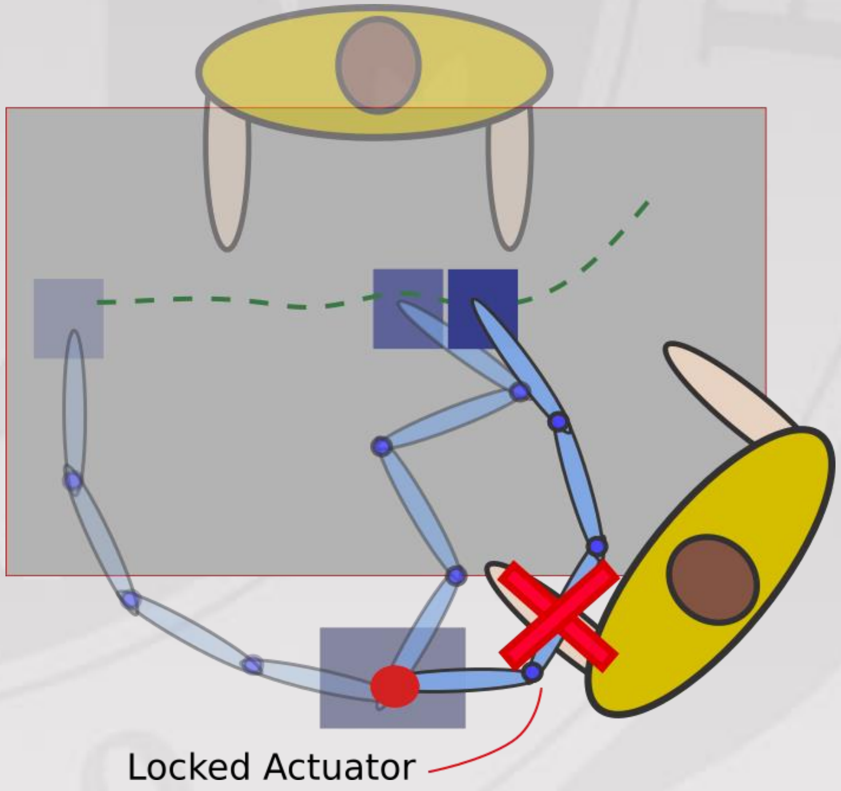


Simulation and results

- Minimize velocity jumps

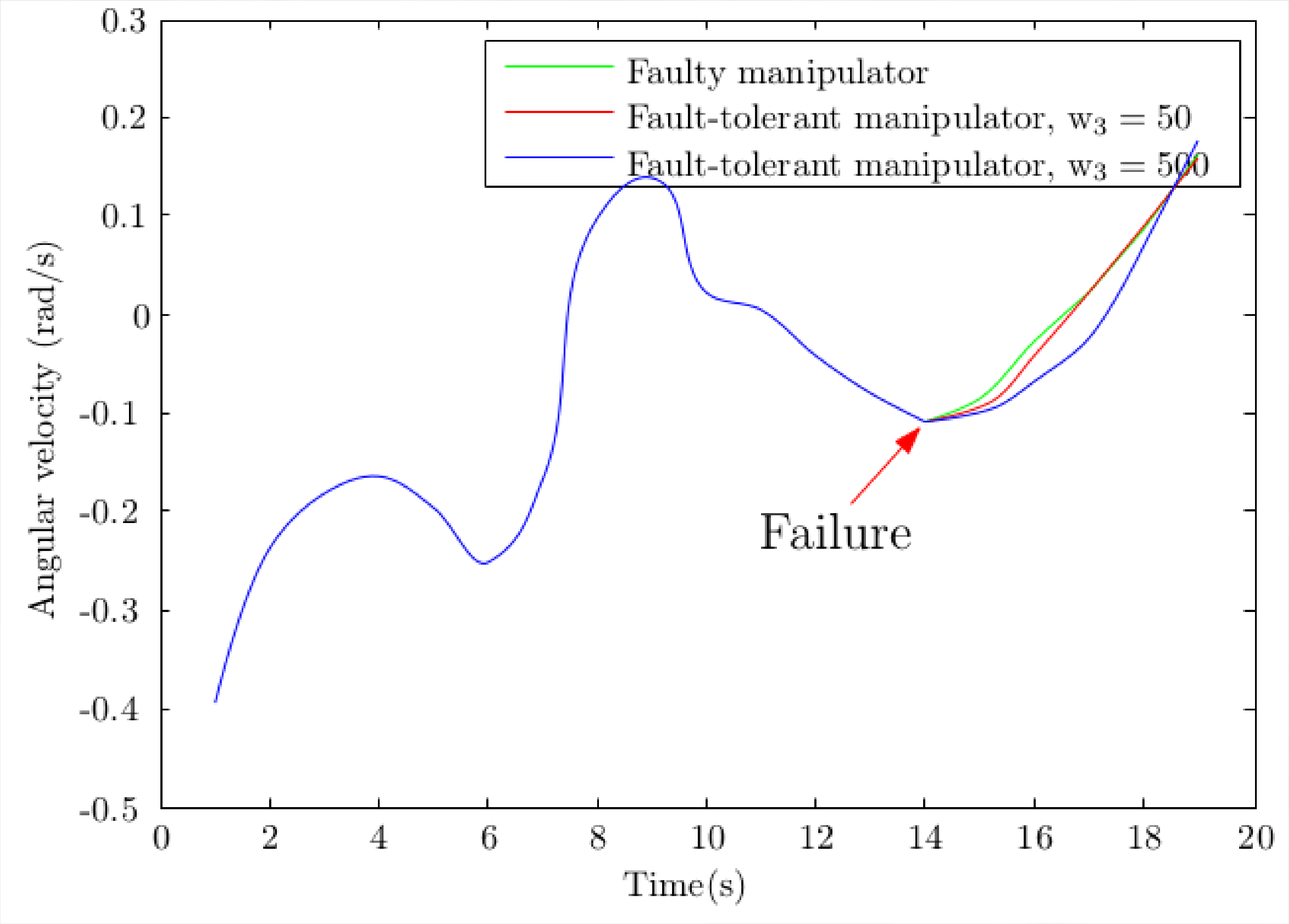


3rd joint

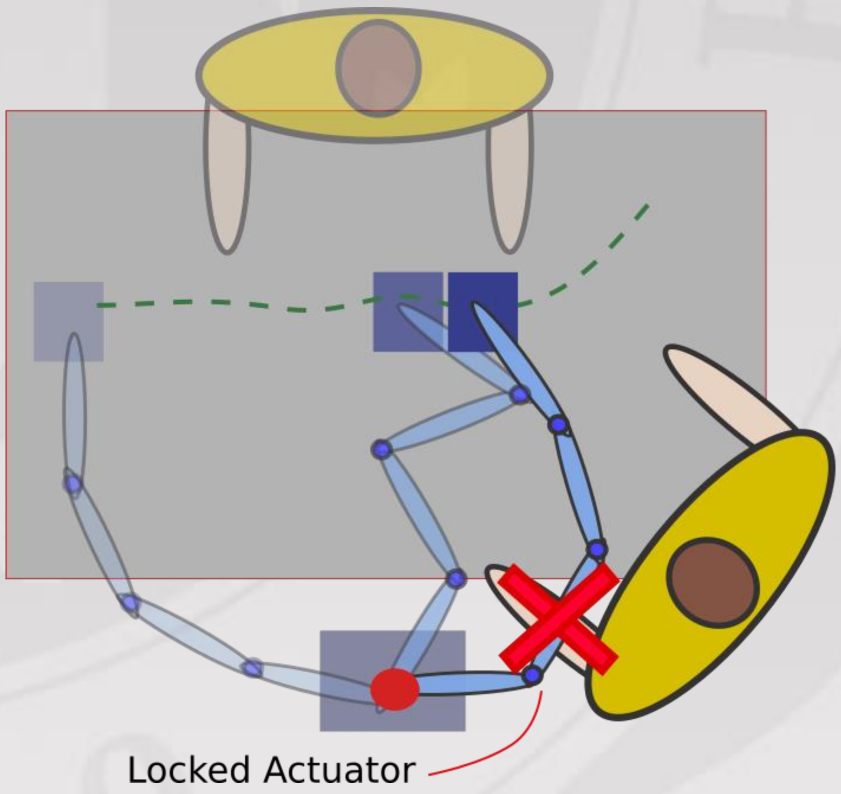


Simulation and results

- Minimize velocity jumps



4th joint



Discussion

- Complete the task safely
- Optimize the joint trajectory
- Avoid having collision with human
- Minimize joints velocity jumps

Improve productivity

Avoid injuries → Improve safety

Conclusion and future work

- Developed an algorithm for improve safety in HRC in advanced manufacturing
- Using motion analysis and machine learning for human motion and intent prediction and perception
- Adding biomechanical constraints, human factors and safety parameters into optimization problem
- Design optimized task assignment between human and robot to improve safety and productivity

Thanks

Questions?